CHAPTER 2
PLANNING AND DESIGN OF STRUCTURES AND EXCAVATIONS TO ACCOMMODATE BACKFILL OPERATIONS

2-1. General. Many earthwork construction problems can be eliminated or minimized through proper design, thorough planning, and recognition of problem areas effecting backfill operations. Recognition and consideration must be given in planning to design features that will make backfilling operations less difficult to accomplish. Examples of problem areas and how forethought in design and planning can help to eliminate backfill deficiencies are presented in the following paragraphs.

2-2. Effect of excavation and structural configuration on backfill operations. Some of the problems encountered in earthwork construction are related to the excavation and the configuration of the structures around which backfill is to be placed. It is the designer's responsibility to recognize these problems and to take the necessary measures to minimize their impact on the backfill operations.

a. Open zones. An open zone is defined as a backfill area of sufficient dimensions to permit the operation of heavy compaction equipment without endangering the integrity of adjacent structures around which compacted backfill operations are conducted. Figure 2-1 shows examples of open zones. In these zones where large compaction equipment can operate, it is generally not too difficult to obtain the desired density if appropriate materials and proper backfill procedures are used. For areas that can be economically compacted by heavy equipment, the designer can avoid problems by including in the design provisions sufficient working space between structures or between excavation slopes and structures to permit access by the heavy compaction equipment. Generally, a working space of at least 12 feet between structure walls and excavation slopes and at least 15 feet between structures is necessary for heavy equipment to maneuver. In addition to maneuvering room, the designer must also consider any adverse loading caused by the operation of heavy equipment too close to structure walls, as discussed in paragraph 2-3d.

b. Confined zones. Confined zones are defined as areas where backfill operations are restricted to the use of small mechanical compaction equipment (fig. 2-2) either because the working room is limited or because heavy equipment (fig. 2-1) would impose excessive soil pressures that could damage the structure. Most deficiencies in compacted backfill around subsurface structures have occurred in confined zones where required densities are difficult to achieve because of restricted working room and relatively low compaction effort of equipment that is too lightweight. The use of small equipment to achieve required compaction is also more expensive than heavy equipment since thinner lifts are required. However, because small compaction equipment can operate in spaces as narrow as 2 feet in width, such equipment is necessary to achieve the required densities in some areas of most backfill projects. Therefore, the designer should plan structure and excavation areas to minimize the use of small compaction equipment.

c. Structure configuration. The designer familiar with backfilling operations can avoid many problems associated with difficult to reach confined zones, which are created by structural shapes obstructing the placement and compaction of backfill, by considering the impact of structural shape on backfill operations. In most cases, structural shapes and configurations that facilitate backfill operations can be used without significantly affecting the intended use of the structure.

(1) *Curved bottom and wall structures*. Areas below the spring line of circular, elliptical, and similar shaped structures are difficult to compact backfill against because compaction equipment cannot get under the spring line. If possible, structures should be designed with continuously curved walls and flat floors such as in an igloo-shaped structure. For structures where a curved bottom is required to satisfy the intended function, it may be advisable for the designer to specify that a template shaped like the bottom of the structure be used to guide the excavation below the spring line so that uniform foundation support will be provided.

(2) *Complex structures*. Complex structures have variable shaped walls and complex configurations in plan and number of levels. These structures can also be simple structures interconnected by access shafts, tunnels, and utility conduits. Because of their irregular shapes and configurations the different types of structures significantly increase excavation and backfill problems.

(*a*) Typical examples of complex structures are stepped multilevel structures and multichambered structures with interconnecting corridors (fig. 2-3). Complex structures are generally more difficult to

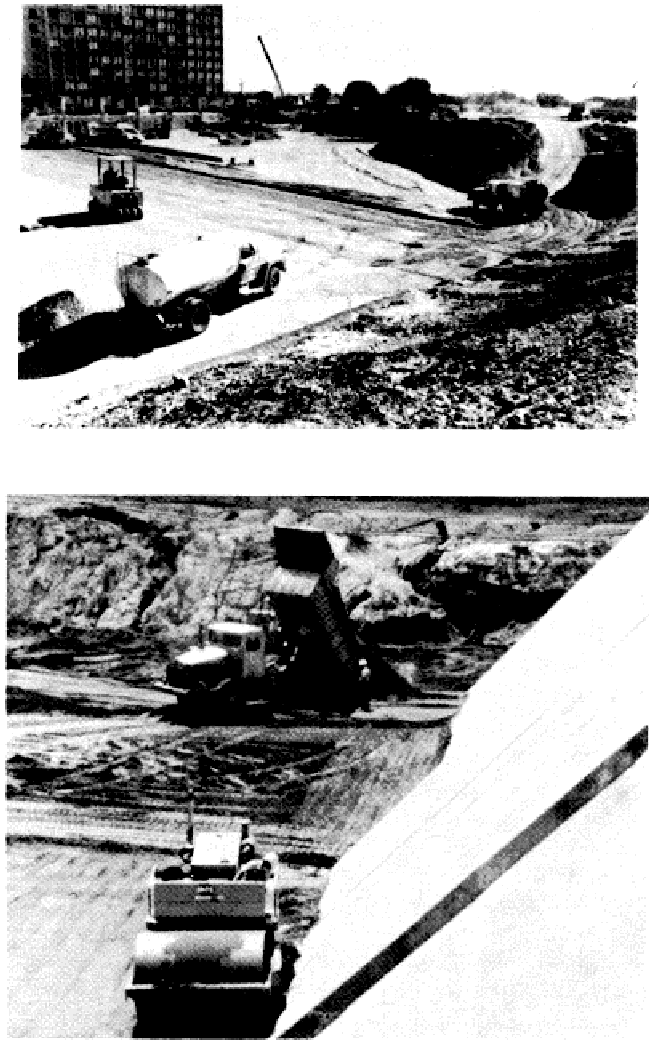


Figure 2-1. Open backfill zones.

compact backfill around and are more likely to have settlement problems (para 2-3a). Although the multilevel step structure (fig. 2-3a) is not particularly difficult to compact backfill around, at least for the first level, the compaction of backfill over the offset structure will generally require the use of small equipment. Small equipment will also be required for compaction of backfill around and over the access corridor and between the two chambers (fig. 2-3b). Where possible, the design should accommodate intended functions into structures with uniformly shaped walls and a simple configuration.

(b) Where structures of complex configurations are necessary, construction of a three-dimensional model during the design and planning phases will be extremely beneficial. From the model, designers can more easily foresee and eliminate areas in which it would be difficult to place and compact backfill.

d. Service conduits. Since compaction of backfill is difficult around pipes and conduits, utility lines should be grouped together or placed in a single large conduit where feasible rather than allowed to form a haphazard maze of pipes and conduits in the backfill. Utility lines should be run either horizontally or vertically wherever possible. Plans for horizontally run appurtenances, such as utility lines, access tunnels, and blast-delay tubing, should be coordinated with the excavation plans so that wherever feasible these appurtenances can be supported by undisturbed soils rather than by compacted backfill.

e. Excavation plans. The excavation plans should be developed with the backfill operations and the structure configurations in mind. The excavation and all completed structures within the excavation should be conducive to good backfill construction procedures, and access should be provided to all areas so that compaction equipment best suited to the size of the area can be used. The plans for excavation should also provide for adequate haul roads and ramps. Positive excavation slopes should be required in all types of soil

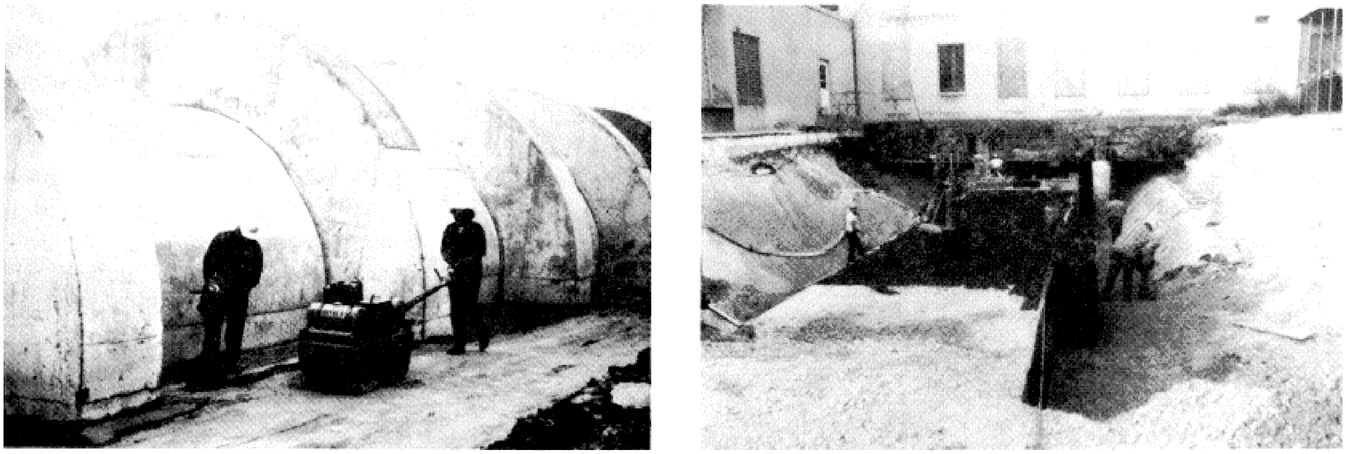
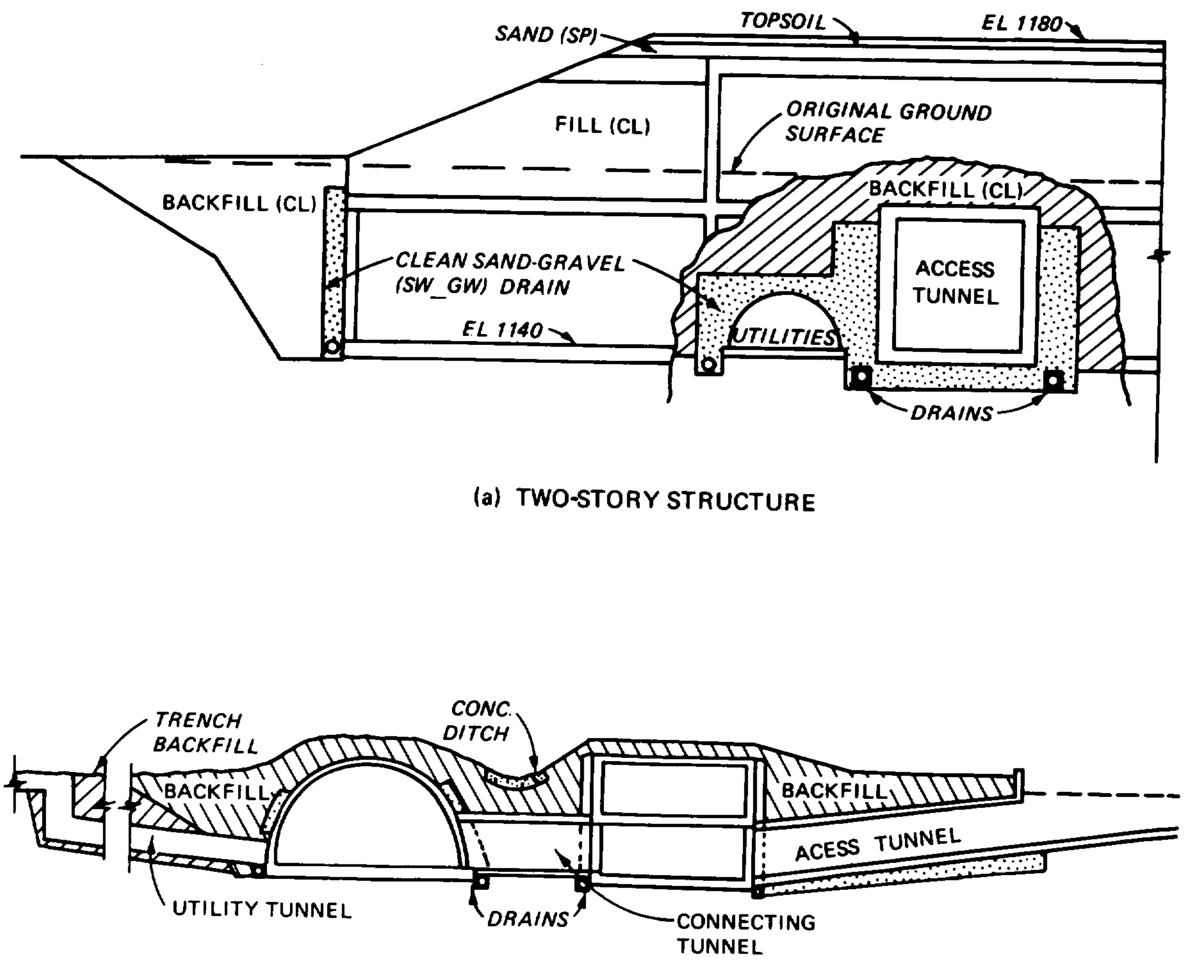


Figure 2-2. Confined backfield zones.



(a) TWO-STORY STRUCTURE

(b) CONNECTING STRUCTURES

Figure 2-3. Complex structures.

deposits to facilitate compaction of backfill against the slope and to ensure good bond between the backfill and the excavation slopes. Loose material should be removed from the excavation slopes; in some cases, benches may be required to provide a firm surface to compact backfill against.

f. Lines and grades. Care should be exercised in planning lines and grades for excavation to ensure that uniform, adequate support is provided at the foundation level of important structures. Generally, foundations consisting of part backfill and part undisturbed materials do not provide uniform bearing and should be avoided wherever possible. The foundation should be overexcavated where necessary, and backfilled with compacted select material to provide uniform support for the depth required for the particular structure. Where compacted backfill is required beneath a structure, the minimum depth specified should be at least 18 inches.

g. Thin-walled metal structures. Thin-walled, corrugated metal structures are susceptible to deflections of structural walls when subjected to backfill loads. Adverse deflections can be minimized by planning backfill operations so that compacted backfill is brought up evenly on both sides of the structure to ensure uniform stress distribution. Temporary surcharge loads applied to the structure crown may also be required to prevent vertical distortions and inward deflection at the sides.

2-3. Backfill problem areas. Other features that have the potential to become problem areas are discussed in the following paragraphs. These potential problem areas have to be considered during the planning and design phases to minimize deficiencies in structure performance associated with backfill placement and to make backfilling operations less difficult.

a. Settlement and downdrag. In the construction of underground structures and particularly missile-launch-site facilities, tolerances to movement are often considerably less than those in normal construction.

The design engineer must determine and specify allowable tolerances in differential settlement and ensure that differential settlement is minimized and/or accommodated. Settlement analysis procedures are outlined in TM 5-818-1/AFM 88-3, Chapter 7. See appendix A, References.

(1) *Critical zones*. Critical backfill zones are those immediately beneath most structures. Consolidation and swelling characteristics of backfill materials should be thoroughly investigated so that materials having unfavorable characteristics will not be used in those zones. Some settlement can be expected to take place, but it can be minimized by requiring a higher than normal compacted density for the backfill. Cohesive backfill compacted at a water content as little as 3 to 4 percentage points below optimum may result in large settlements caused by collapse of nonswelling soil material or heave of swelling materials upon saturation after construction. Compacting cohesive backfill material at optimum water content or slightly on the wet side of optimum generally will reduce the amount of settlement and swelling that would occur. The reduction should be confirmed by consolidation and swell tests on compacted specimens (para 3-2b(4)).

(2) *Service conduits*. Settlement within the backfill around structures will also occur. A proper design will allow for the estimated settlement as determined from studies of consolidation characteristics of the compacted backfill. Where service conduits, access corridors, and similar facilities connect to the structure oversize sleeves, flexible connections and other protective measures, as appropriate, may be used to prevent damage within the structure.

(3) *Differential settlement*. Complex structures are more susceptible to differential settlement because of the potential for large variations in loads carried by each component foundation. In the multilevel stepped structure (fig. 2-3a), the foundation supporting the lower level offset component must also support the volume of backfill over that part of the structure. Measures must be taken to ensure that the proper functioning of all elements is not hampered by differential settlement. The increased cost of proper design and construction where unusual or difficult construction procedures are required is insignificant when compared with the cost of the structure. The cost of remedial measures to correct deficiencies caused by improper design and construction usually will be greater than the initial cost required to prevent the deficiencies.

(4) *Downdrag*. In addition to conventional service loads, cut and cover subsurface structures are susceptible to downdrag frictional forces between the structure and the backfill that are caused by settlement of the backfill material adjacent to and around the structure. Downdrag loads can be a significant proportion of the total vertical load acting on the structure and must be considered in the structure settlement analysis. Structure-backfill friction forces may also generate significant shear forces along the outer surface of structures with curve-shaped roofs and walls. The magnitude of the friction forces depends upon the type of backfill, roughness of the structure's surface, and magnitude of earth pressures acting against the structure. Techniques for minimizing downdrag friction forces generally include methods that reduce the structure surface roughness such as coating the structure's outer surface with asphalt or sandwiching a layer of polyethylene sheeting between the structure's outer surface and fiberboard (blackboard) panels. Backfill settlement and associated downdrag can also be minimized

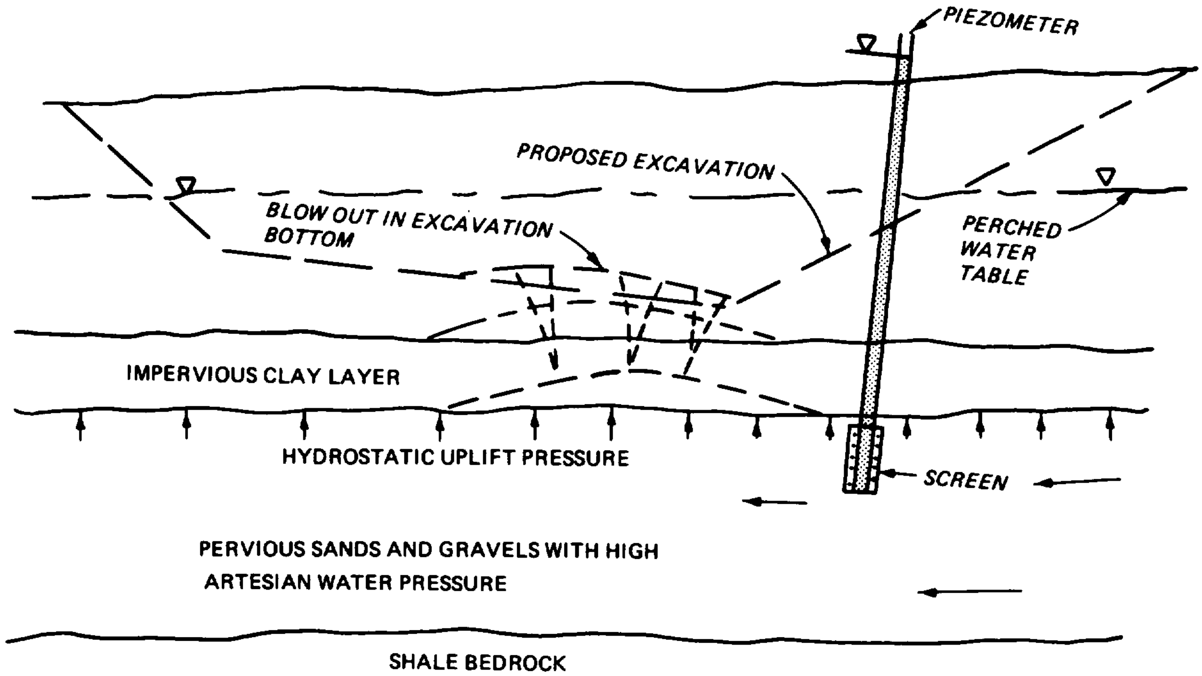


Figure 2-4. Excavation subject to bottom heave.

by requiring higher backfill densities adjacent to the structure.

b. Groundwater. Groundwater is an important consideration in planning for construction of subsurface structures. If seepage of groundwater into the excavation is not adequately controlled, backfilling operations will be extremely difficult. The groundwater level must be lowered sufficiently (at least 2 to 3 feet for granular soils and as much as 5 to 10 feet for fine-grained soils below the lowest level of backfilling) so that a firm foundation for backfill can be established. If the level is not lowered, the movement of hauling or compaction equipment may pump seepage water through the backfill, or the initial backfill layers may be difficult to compact because of an unstable foundation. Since the proper water content of the backfill is essential for achieving proper compaction, prevention of groundwater seepage into the excavation during backfilling operations is mandatory. Figure 3-14 of EM 1110-2-1911 shows a method for dewatering rock foundations.

(1) The contractor is generally responsible for the design, installation, and operation of dewatering equipment. The Corps of Engineers is responsible for specifying the type of dewatering system and evaluating the contractor's proposed dewatering plan. Since the dual responsibility of the contractor and the Corps relies on a thorough understanding of groundwater conditions, inadequate dewatering efforts can be mini minimized by adequate planning and implementation of groundwater investigations.

(2) The possibility of hydraulic heave in cohesive material must also be investigated to ensure stability of the excavation floor. Hydraulic heave may occur where an excavation overlies a confined permeable stratum below the groundwater table (fig. 2-4). If the upward hydrostatic pressure acting at the bottom of the confining layer exceeds the weight of overburden between the bottom of the excavation and the confining layer, the bottom of the excavation will rise bodily even though the design of the dewatering system is adequate for control of groundwater into the excavation. To prevent heave, the hydrostatic pressure beneath the confined stratum must be relieved.

(3) Subsurface structures located in part or wholly below the groundwater table require permanent protection against groundwater seepage. The type of protection may range from simple impermeable barriers to complex permanent dewatering systems.

(4) Dewatering and groundwater control procedures are described in TM 5-818-5/NACFAC P-418/AFM 88-5, Chapter 6.

c. Gradation and filter criteria for drainage materials. Groundwater control is often accomplished by ditches positioned to intercept the flow of groundwater and filled with permeable granular material. The water is generally collected in perforated pipes located at the bottom of the ditch and pumped to a suitable discharge area. Such drainage systems are referred to as filter drains. The gradation of the granular filter material is critical for the functioning of the system. Selection of the proper gradation for the filter material is dependent upon the gradation of the material that is being drained. Drainage of silts and clays usually requires a graded filter made up of several layers of granular material with each layer having specific requirements for maximum grain size and gradation. Details on the design of filter drains are presented in TM 5-818-5/NAVFAC P-418/AFM 88-5, Chapter 6.

(1) *Selected material*. If materials at the jobsite do not meet the designed filter requirements, select material must be purchased from commercial sources and shipped to the jobsite. Filter material must be stockpiled according to gradation. For graded filter systems, the materials must be placed with care to minimize mixing of individual components.

(2) *Filter cloths*. Both woven and nonwoven filter cloths, which have been found satisfactory for use as a filter media for subsurface drains, are available. When granular filter materials are not economically available, a single wrap of filter cloth around a pipe may be used in lieu of a coarser backfill. When available granular filter material is too coarse to satisfy filter criteria for the protected soil, a single layer of filter cloth may be used adjacent to the protected soil. To reduce the chance of clogging, no filter cloth should be specified with an open area less than 4 percent and or equivalent opening size (EOS) of less than the No.100 sieve (0.0059 inch). A cloth with openings as large as allowable should be specified to permit drainage and prevent clogging. Additional information on airfield drainage is contained in TM 5-820-2/AFM 88-5, Chapter 2.

(3) *Other uses*. Filter cloth can also provide protection for excavated slopes and serve as a filter to prevent piping of fine-grained soils. In one project, sand was not available for backfill behind a wall and coarse gravel had to be used to collect seepage. The filter cloth used to protect the excavated slope served as a filter against piping of the natural silty clay under seepage gradients out of the excavated slope after the coarse gravel backfill was placed.

d. Earth pressures. The rationale design of any structure requires the designer to consider all loads acting on the structure. In addition to normal earth pressures associated with the effective presdsure distribution of the backfill materials, subsurface cut-and cover structures may also be subjected to surcharge loads caused by heavy equipment operating close to the structure and by increased permanent lateral earth pressures caused by compaction of backfill material with heavy equipment. Procedures for predicting normal earth pressures associated with the effective pressure of backfill materials are discussed in TM 5-818-1/lAFM 88-3, Chapter 7, EM 1110-2-2902, and EM 1110-2-2502.

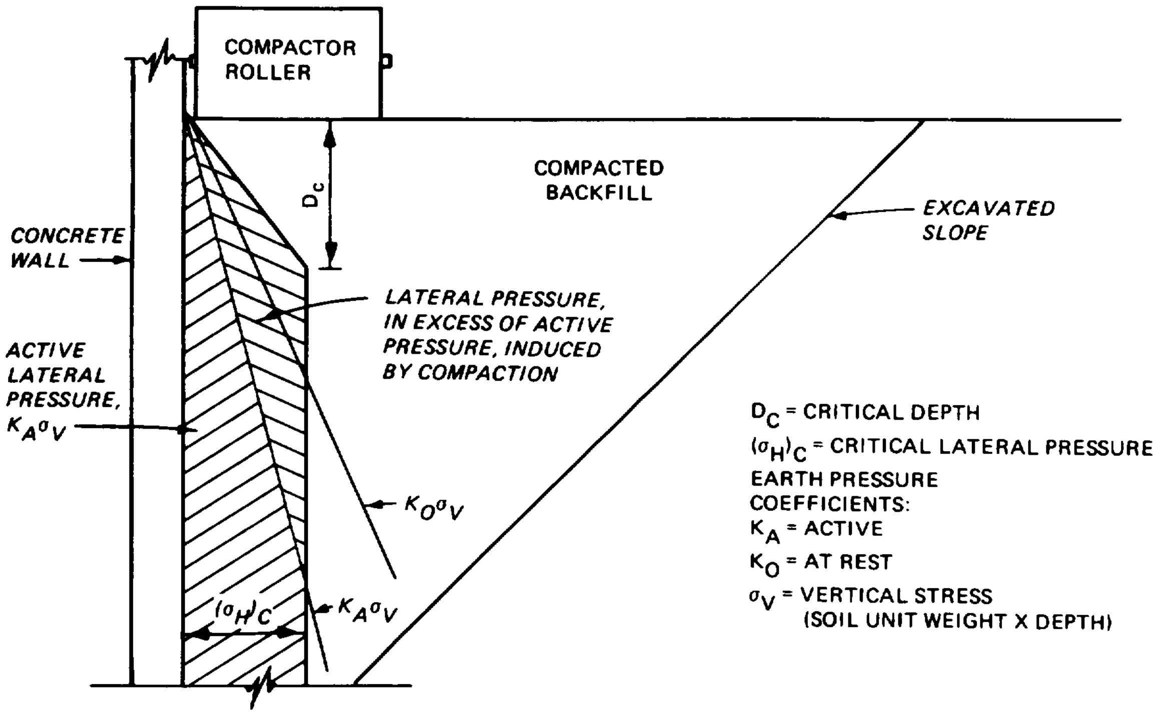
(1) Exact solutions for surcharge earth pressures generated by heavy equipment (or other surcharge loads) do not exist. However, approximations can be made using appropriate theories of elasticity such as Boussinesq's equations for load areas of regular shape or Newmark's charts for irregular shaped load areas as given in NAVFAC DM-7. As a conservative guide, heavy-equipment surcharge earth pressures may be minimized by specifying that heavy compaction equipment maintain a horizontal distance from the structure equivalent to the height of the backfill above the structure's foundation.

(2) Compaction-induced earth pressures can cause a significant increase in the permanent lateral earth pressures acting on a vertical wall of a structure (fig. 2-5a). This diagram is based on the assumption that the equipment can operate to within 6 inches of the wall. Significant reductions in lateral pressures occur as the closest allowable distance to the wall is increased (fig. 2-5b). For an operating distance 5 feet from the wall, the induced horizontal earth pressure is much less than that caused by the backfill. The magnitude of the increase in lateral pressure is dependent, among other factors, on the effective weight of the compaction equipment and the weight, earth pressure coefficient, and Poisson's ratio of the backfill material. Compaction-induced earth pressures against walls are also described in TM 5-818-1/AFM 88-3, Chapter 7, and EM 1110-2-2502.

(3) The designer must evaluate the economics of the extra cost of structures designed to withstand very close-in operation of heavy compaction equipment versus the extra cost associated with obtaining required compaction of backfill in thin lifts with smaller compaction equipment. A more economical alternative might be to specify how close to the walls different weights of compaction equipment can be operated.

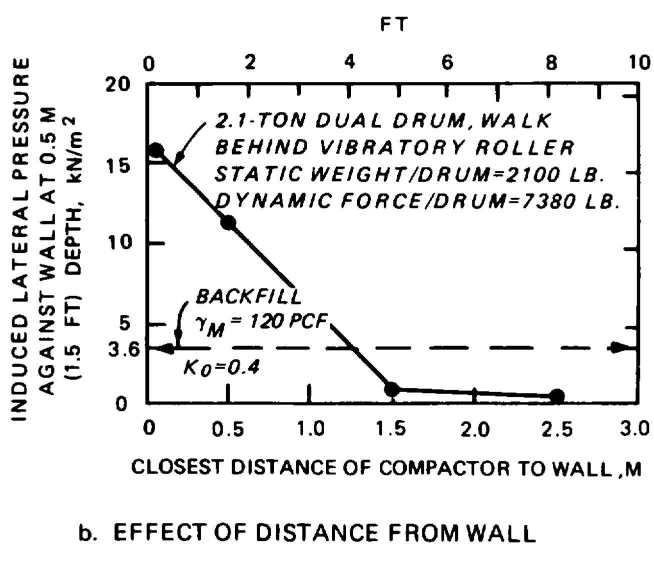
(4) One method of reducing lateral earth pressures behind walls has been to use about 4 feet of uncompacted granular (sand or gravel) backfill above the base of the wall. Soil backfill can then be compacted in layers above the granular backfill. Compression of the granular material prevents the buildup of excessive lateral pressures against the wall.

e. Structural backfill. Structural backfill is defined as the compacted backfill required over and around a structure to prevent damage from heavy equipment operating over or near the structure. This backfill must be compacted using small compaction equipment, such as mechanical rammers or vibratory-plate compactors, or intermediate size equipment such as walk-behind, dual-drum vibratory rollers. The horizontal and vertical distances from the structure for which structural backfill is required should be deter



COMPACTION EQUIPMENT	CRITICAL DEPTH D_C, FT	$(\sigma_H)_c$ psf
10–TON SMOOTH WHEEL ROLLER	1.9	420
3.2–TON VIBRATORY ROLLER	1.7	400
1.4–TON VIBRATORY ROLLER	1.2	260
400–KG VIBRATORY PLATE	1.5	340
120–KG VIBRATORY PLATE	1.0	240

a. MAXIMUM INDUCED LATERAL PRESSURES



b. EFFECT OF DISTANCE FROM WALL

Figure 2-5. Excess lateral pressure against vertical walls induced by compaction.

mined from estimates of loads acting on the structure caused by heavy equipment and on the strength of the embedded structure members as discussed in d above. A 2-foot cover over small utility conduits and pipes is adequate protection where proper bedding procedures are followed. The minimum cover requirements over larger diameter (6 inches or greater), rapid and flexible pipes are presented in appendix II of TM 5-8204/AFM 88-5, Chapter 4.

f. Slopes and bracing. Where open excavation is planned, consideration should be given to the slopes to which the materials to be encountered can be cut and remain stable. The stability analysis should include the strength of the materials, groundwater conditions, and any surcharge load that may be imposed as the result of stockpiles being placed or equipment operating near the crest of the excavation. Slope stability evaluation procedures are described in TM 5-818-1/AFM 88-3, Chapter 7. Shoring and bracing should be used to support excavation slopes where it is not feasible to excavate to stable slopes (TM 5-818-1/AFM 88-3, Chapter 7). Requirements for shoring and bracing safety are presented in EM 385-1-1.

g. Bedding for curved-bottom structures. Foundations for pipes, conduits, access tunnels, fuel and water storage tanks, and other curved-bottom structures constructed within the backfill are considered critical zones that require special attention. Any bedding material used should be free of stones or other large particles that would lead to nonuniform bearing. One of the most important functions of any bedding procedure is to provide firm support along the full length of the structure. For areas where it is difficult to perform field density control tests because of limited working space, a procedure to ensure that proper compaction is obtained must be employed. Several methods of obtaining adequate bedding are discussed in paragraph 5- 1c (2).

h. Cold weather construction. Cold weather can have a very adverse effect on backfilling operations and can cause considerable delay. If possible, the project should be planned to complete backfilling operations prior to any extended period of freezing temperatures. The contractor and the resident engineer must keep up to date with weather data so that the contractor can plan the equipment and construction force required to meet the construction schedule and to protect the work already accomplished.

(1) The designer must establish definite limitations and requirements regarding placement of backfill when the ambient temperature is below freezing. Most inorganic soils, particularly silts and lean clays, containing 3 percent, by weight, or more of particles finer than 0.02 millimetre in diameter are frost susceptible. Such soils, when frozen in the presence of an available source of water, develop segregated ice in the form of lenses, layers, veins, or masses commonly, but not always oriented normal to the direction of heat loss. The expansion of the soil mass resulting from ice segregation is called frost heave. Frost heave of soil under and against structures can cause detrimental effects, which can be compounded during subsequent thawing by differential movement, loss of density, and loss of shear strength. Soils of this type should not be placed during or immediately prior to freezing temperatures and must not be placed in critical areas. Nonfrost susceptible soils should be used at the finished grade to the depth of frost penetration when the finished grade serves as a load-bearing surface.

(2) Additives, such as calcium chloride, can be used to lower the freezing temperature of soil water, but such additives will ordinarily also change the compaction and water content requirements. Therefore, additives must not be used without prior investigation to determine their effect on compaction and water content requirements. Dry sand or sand-gravel mixtures can be placed satisfactorily when temperatures are below freezing without serious effects.

(3) Protection must be provided for in-place permanent backfill in critical areas, such as those around and under structures and embedded items already placed. To preclude structural damage from possible frost heave, backfill materials around such structures should be insulated with a protective covering of mulch, hay, or straw. In some instances, loose lifts of soil can be used for insulation. However, rock or sand is too porous to provide sufficient insulation and too permeable to resist water penetration. If soil is to be used as an insulating material, a material completely foreign to the permanent fill, such as straw or building paper, should be laid down prior to placement of the insulation fill so that there will be a marked distinction between the permanent and the temporary insulation fills. In this way, when the insulation fill is removed, the stripping limits can be readily discerned.

(4) Flooding of the excavation has also been used successfully to prevent frost penetration of the inplace permanent backfill. However, consideration must be given to possible detrimental effects of saturating in-place backfill and the delay of removing the water at the beginning of the next construction season if it freezes into a solid mass of ice.

(5) Concrete walls and floors of completed structures provide poor insulation for the fill around and beneath these structures. Therefore, these structures should be enclosed as much as possible and kept closed during the winter when construction is halted because of adverse freezing weather. Reinforcing steel protruding from a partially completed structure will conduct cold through the concrete and increase the rate and depth of frost penetration beneath the structure.

Every effort should be made to schedule construction so that this condition will be kept to a minimum, and protection must be required where necessary.

i. Seismic zones. The design considerations for subsurface structures subjected to dynamic loads caused by seismic activity or explosive devices are beyond the scope of this manual. Design details are provided in TM 5-818-1/AFM 88-3, Chapter 7, and ER 1110-2-1806. Specific problems relating to backfill operations are primarily limited to possible potential for dynamically induced liquefaction. Certain materials are particularly susceptible to liquefaction; these include saturated gravels, sands, silts, and clayey sands and gravel. Where these materials are used as backfill, the potential for liquefaction can be minimized by requiring a high degree of compaction, particularly in critical areas such as beneath footings and under the spring line of curved wall structures. The requirements for materials susceptible to liquefaction are discussed in paragraph 3-3d.

2-4. Instrumentation. For important structures of unique design or for structures where the potential for postconstruction distress exists, instrumentation of the structure should be considered. The instrumentation program may include monitoring the amount and rate of settlement, movement of retaining walls and other structural elements, development of stresses within the structure, and development of hydrostatic and earth pressures against the structure. Analysis of the data will furnish a check on design assumptions and indicate what measures must be taken to relieve or correct undesirable conditions before distress develops. Information of this nature can also be of significant value in future design and construction.

a. Requirements. Specific requirements for instruments are ruggedness, reliability over the projected service life, and simplicity of construction, installation, and observation. Other important considerations in selecting the type of instruments are cost and availability. Manufacturers of devices considered for installation should be asked to provide a list of projects on which their devices have been installed, and previous users of new equipment should be contacted to ascertain their operating experiences.

b. Installation and observation of instrumentation. A rational instrumentation program must use the proper type of instruments and have the instruments installed properly at critical locations. Valid readings often depend on techniques and procedures used in installing and observing the instrumentation.

(1) Schedules for observations are generally established by the design office. Initial observations should be checked to assure their validity and accuracy, since these readings usually form the basis to which subsequent observations are related. Observations should be plotted immediately after each set of readings is taken and evaluated for reasonableness against previous sets of readings. In this way, it is often possible to detect errors in readings and to obtain check readings before significant changes in field conditions occur.

(2) EM 1110-2-1908 discusses in detail various types of instrumentation devices; procedures for installation, observation, and maintenance; collection, recording, analysis, and reporting of data; and possible source of error and causes of malfunctions.

2-5. Optimum cost construction. The designer should consider all details of the construction process to ensure a safe and operational facility at the lowest possible cost.

a. Energy requirements. The consideration of energy requirements is important not only for economical reasons but also for the critical need to conserve energy wherever possible. It should not be the intent of the design engineer to unduly restrict the competitive nature of current contractural procedures. Nevertheless, there are certain alternatives that the designer may specify that potentially could lead to more energy efficient construction with cost saving being reflected in bid prices. Some of the possible alternatives that should be considered are discussed below.

(1) Sources of suitable select backfill material should be located as close to the project site as possible. The source may be either a borrow area or a commercial vendor.

(2) Hauling routes to and from the source of backfill and the project site should follow the most direct route.

(3) Only compaction equipment that will compact the specific backfill to the required density in an efficient manner should be approved for use. For large projects, the designer may require that the contractor demonstrate the capabilities of the equipment he intends to use prior to construction.

(4) If possible, material from excavations or within the immediate vicinity of the project site should be used as backfill, even though such material may be marginally suitable. The engineering characteristics of marginal material may be enhanced by the use of additives (para 3-3d).

(5) The energy requirements for adequate cold weather protection of construction personnel and structures can be considerable. For project sites subject to seasonal cold weather, construction should not, if possible, be scheduled during extreme cold weather periods.

b. Value engineering. Potential cost savings may be realized by encouraging the contractor to participate in value engineering, whereby the contractor shares any project saving derived from realistic cost-saving suggestions submitted.